

Measurements of Aerosol properties in the MABL Using Polarization Nephelometry

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Document Number: N00014-00-F-0005

http://www.onr.navy.mil/sci_tech/ocean/onrpgahk.htm

LONG-TERM GOALS

The long-term goal is to develop and evaluate polarization sensitive instrumentation to improve the measurement and understanding of the properties of aerosols in the Marine Atmospheric Boundary Layer (MABL). Aerosol components include sea salt containing aerosols, sulfates, continental aerosols, diesel and fire smoke. Accurate characterization of the aerosols in the MABL on a real-time basis requires data acquisition equipment and rapid interpretation of remotely sensed data. Light scattering techniques provide the most practical and rapid *in situ* means to characterize these aerosols. However, traditional light scattering measurements do not use all the information available in the light scattered from the aerosol particles, specifically polarization data and only LIDAR currently provides for long range probing of the atmosphere. Angle dependent measurements of the Mueller scattering matrix provide the most complete optical description of the aerosols. Once obtained, the detailed knowledge of aerosol optical properties enables accurate prediction of light propagation in the MABL. These predictions can determine the effects of aerosols on visibility and the propagation of coherent and incoherent light. The information can also be used to evaluate the design and operation of polarizing optics to maximize imaging or detection system performance.

OBJECTIVES

Our objective is to test the concept of bistatic polarization-sensitive nephelometry for characterizing atmospheric aerosols.^{1,2} The first step was to deploy two polarization-sensitive light scattering instruments at a field site to characterize MABL aerosols. After the feasibility and characteristics of the bistatic technique were established, we evaluated extending the approach to use as a remote probe of aerosol particles at significant distances. If feasible, it should be possible to use the technique to map the characteristics of MABL aerosols at significant distances from a ship or shore based measurement system. Successful application of this technique would allow prediction of the light propagation, visibility, and scattering characteristics of MABL aerosols.

APPROACH

To evaluate this approach in the MABL and determine the character of the data, measurements were carried out at a mid-pacific beach site using an existing Bistatic Nephelometer and the Particle Scatterometer to measure marine aerosol properties. In conjunction with the SEAS marine aerosol

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 30 OCT 2001		2. REPORT TYPE		3. DATES COVERED 00-00-2001 to 00-00-2001	
4. TITLE AND SUBTITLE Measurements of Aerosol properties in the MABL Using Polarization Nephelometry				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Lawrence Berkeley National Laboratory,,University of California,,Berkeley,,CA, 94720				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

campaign, the instruments were used to measure the MABL aerosols including sea salt aerosols produced by a coral reef and low-intensity breaking waves on the nearby beach. The bistatic instrument, using an independently directed light source and detector separated by an appropriate distance, allows aerosol characterization at the volume defined by the intersection of the optics. The main tasks were to investigate the nature of the signals produced by the instruments and determine their effectiveness in this application.

WORK COMPLETED

This year we carried out an analysis of the data taken in Hawaii and built and tested a large-scale bistatic polarization nephelometer. The existing instruments were used to obtain the phase function for the marine environment and determine the angle dependent and temporal features of the polarization-modulated light scattering signals. The rather unusual temporal character of the scattered light from these aerosols required development of a new signal processing analysis to utilize the polarization dependent high frequency components present in the raw data. In addition, a bistatic nephelometer was designed and built to be capable of probing aerosols from greater distances (meters to tens of meters). This instrument was tested and evaluated in the laboratory.

RESULTS

Two instruments were used in this study; the Bistatic Nephelometer³ and the Particle Scatterometer.⁴ The principles of operation of both instruments are very similar but are implemented in different geometries. The Particle scatterometer samples the aerosol by drawing it into a sample region illuminated by the laser and viewed by 12 detectors spaced at 10-degree intervals in scattering angle. A port located directly below the aerosol-input tube draws the sample through the sensing region. The detectors are scanned with a multiplexer at a rate of about one Hz. The raw and processed data is stored on the computer for further analysis.

The Bistatic Nephelometer is an instrument modified from one developed earlier for measurements in sea ice⁴. In this case, both the laser beam and the detector are pointed independently providing a means to probe the sample space in situ. For these measurements, we chose to keep the laser fixed and allow the detector to scan along the laser beam. In both instruments, the scattering volume is defined by the intersection of the laser beam and detector optics. Since the laser beam was not expanded, the effective scattering volume was relatively small (the laser beam diameter was less than 1 mm – the viewing optics had a field of view of about 5 degrees. As we shall see, this small scattering volume had significant consequences on the character of the data.

Both instruments rely on the polarization modulation of laser light before striking the aerosol particles in the sensing region. Light from a 50 mW Nd-YAG cw laser at 532 nm wavelength is modulated at a 50 kHz rate by passing it through a vibrating fused silica plate (Hinds Photoelastic Modulator). The strain-induced birefringence in the silica plate produces a light beam that is constant in intensity but with phase varying from linear to elliptical polarization. When this modulated light beam is scattered from particles it has three main components, a dc (time constant) component proportional to the phase function of the scatterers and time varying components at 50 and 100 kHz. With suitable polarizers in front of the detectors these components become proportional to three components of the Mueller matrix representing the scatterers. The detailed Mueller matrix formulation and principle of the measurement are discussed elsewhere.^{5,6}

The ac components of the signal are synchronously detected using digital lock-in amplification implemented in a PC computer using software developed at LBNL. Once the three Mueller matrix elements S_{11} , S_{12} , and S_{34} are measured, S_{11} and the normalized values of S_{12} and S_{34} are plotted as a function of angle on the windows-based data acquisition and analysis system. These results are saved in computer memory and can be analyzed to determine the size and refractive index of the aerosol particles. This is accomplished on line by matching Mie calculations of a particle size distribution with the measured results. The Levenburg-Marquart optimization approach is used to obtain a best fit to all three curves representing the matrix elements simultaneously. This approach is much more robust in its determination of the optical properties of the scatters than techniques that rely on fitting only the phase function (scattered light intensity vs. angle). Fig. 1 illustrates the graphical output for the Particle Scatterometer with a point for each detector and the smooth line showing the best fit of the data. The example shown is for diesel exhaust.

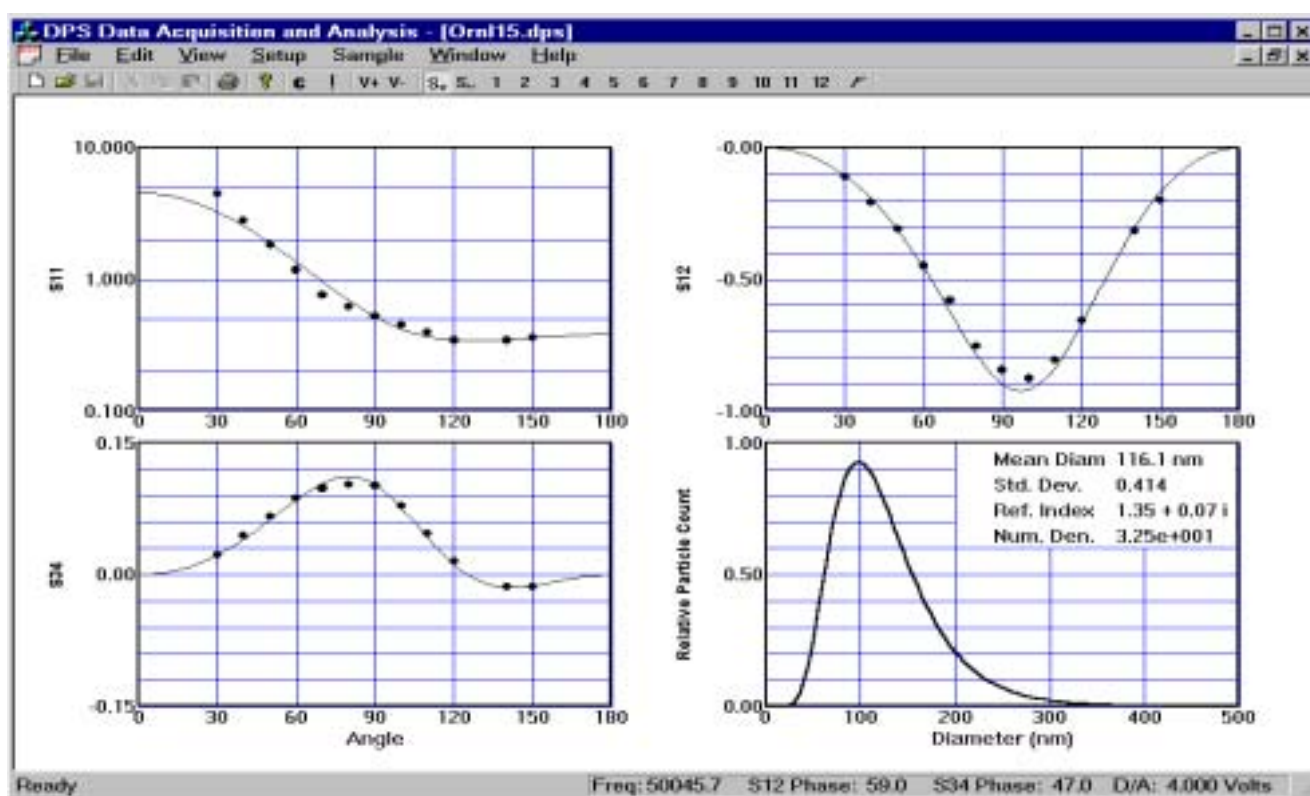


Figure 1. Particle Scatterometer output (represented by the dots) and best-predicted Mie calculation fit (solid lines). The results of the fit and size distribution are given in the lower right display.

The Particle Scatterometer was developed to analyze aerosols in cases where many particles are in the beam simultaneously. In this case, a time-averaged signal exists corresponding to the combined scattering from all the particles. Thus, the continuous data record can be analyzed as an ensemble average and the Mie fitting routine can be used to represent accurately a particle size distribution. However, the combination of small scattering volume and low number density of large salt water aerosols at the SEAS site results in stochastic rather than averaging behavior of the scattered light signal. A typical data record of the scattered intensity as a function of time at 90-degree scattering

angle is shown in Fig. 2a and its Fourier transform in Fig. 2b. Each pulse in Figure 2a represents a particle moving through the scattering volume.

When the data occurs stochastically as illustrated in Fig. 2a, the lock-in amplifier must respond to time averaged components of 50 and 100 kHz. It can be seen that the spectral energy at 50 and 100 kHz is clearly visible with the low frequency and noise appearing in the large low frequency component (<10 kHz) shown in Fig. 2b. Fig. 3 illustrates a modeled signal pulse with an envelope which simulates the scattered light time history resulting from the particle passing through the Gaussian intensity profile of the laser beam. The figure shows the numerical simulation of a single pulse with 25% modulation of the 50 and 100 kHz components which represent the polarization properties of the particle. Fig. 3b shows its Fourier transform which should be compared to Fig. 2b. The total intensity (S_{11}) is measured properly as the average over all the pulses and is the average intensity at each scattering angle. As illustrated in Fig. 3 it can be seen that in the model case the 25% high frequency modulations are accurately recovered by the FFT. However, in the experimental measurements the presence of noise attenuates the response at 50 and 100 kHz. The most obvious solution is to increase the scattering volume so that the stochastic nature of the signal is minimized.

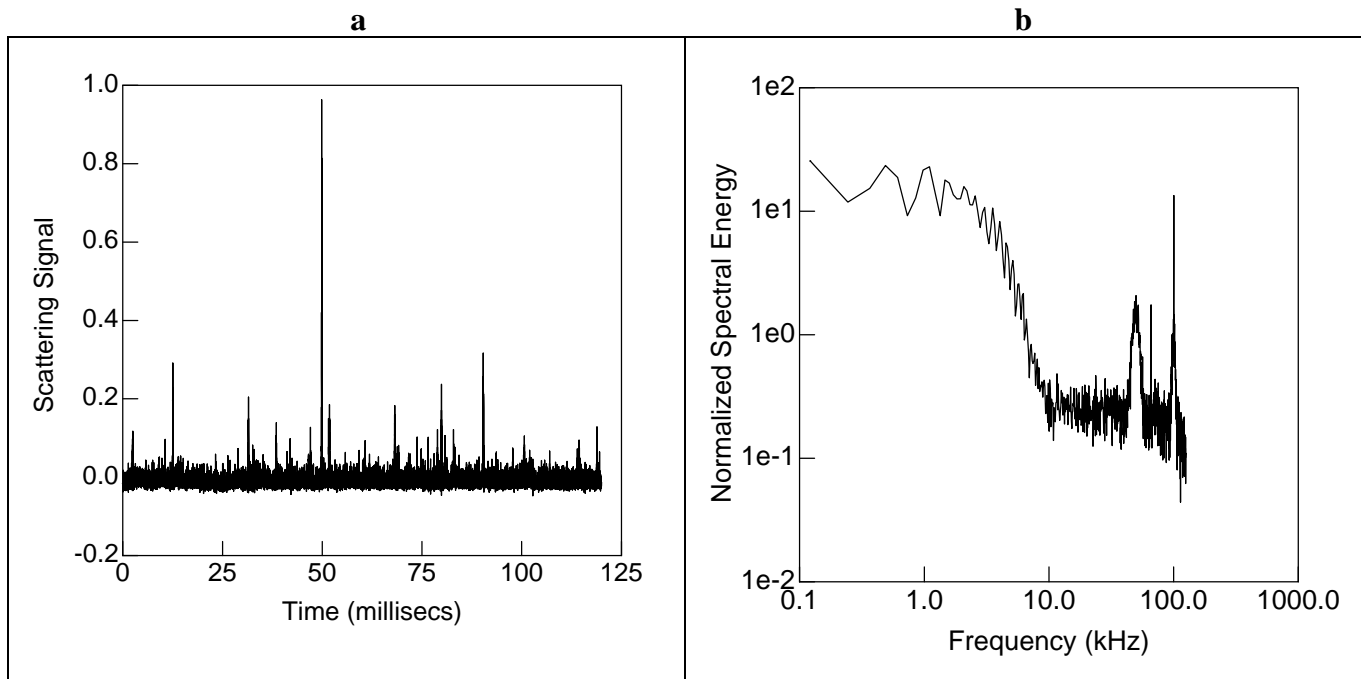


Figure 2. a) Illustrates the nature of the signals from individual aerosol particles moving through the scattering volume, b) the Fourier transform of the data.

A larger scale bistatic nephelometer was built to both increase the scattering volume as well as the scale of the measurement to enable more remote sensing of the aerosols. The new instrument utilized a much higher-powered laser (several watts in the visible region) and an 8-inch reflecting telescope to increase the light gathering power. The object was approximately to match the f-number of the new system to that of the DPS measurements. New traversing and data acquisition software were written and the new system was calibrated and tested in the laboratory to determine its sensitivity and operating parameters. The instrument worked well with artificial aerosol but had very low signal-to-

noise ratio for background aerosols that were judged to be more scattering than marine aerosols of the type measured in Hawaii. It was concluded that the system would work in high aerosol loadings but both more power and light gathering capability would be required for marine aerosols of the type measured in Hawaii.

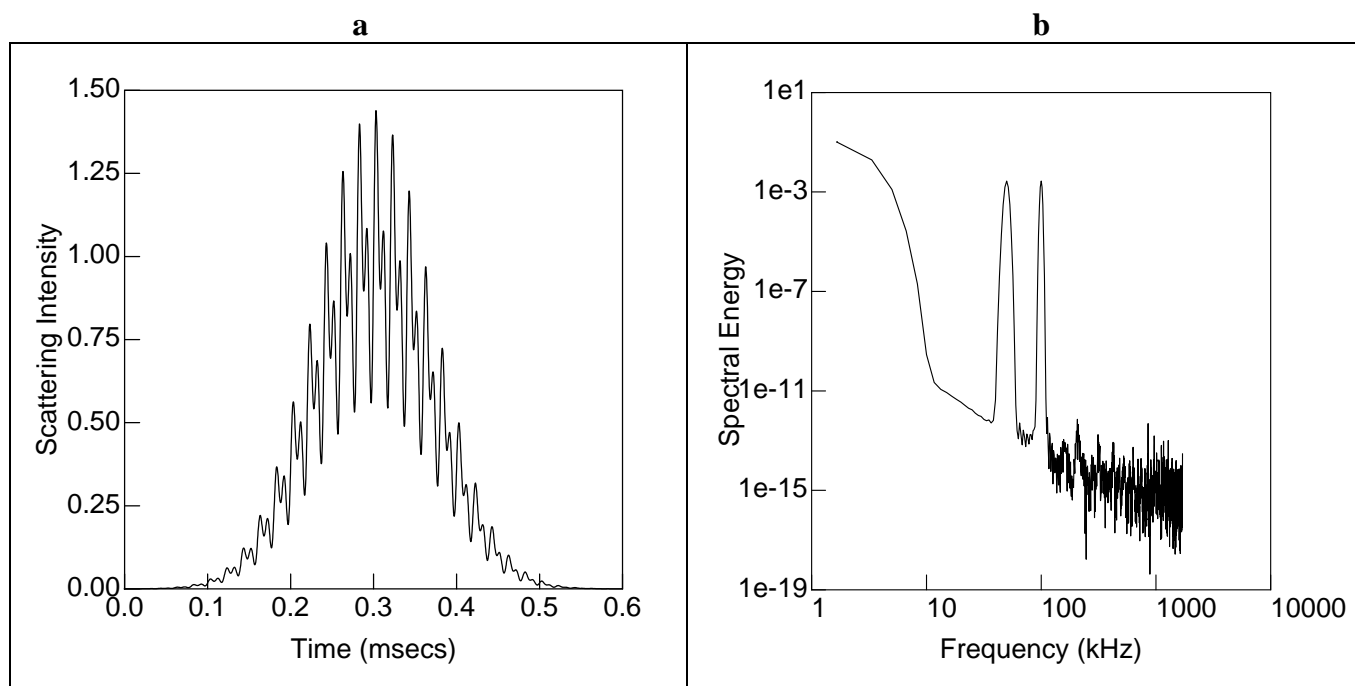


Figure 3. Numerical Simulation of single pulse data: a) Gaussian beam profile and polarization modulation b) Fourier transform of figure 3a.

IMPACT/APPLICATIONS

A major finding of the project was to determine that polarization sensitive bistatic probing light scattering measurements are feasible but that the instrument requires a high power pulsed laser and optics with large light collecting capability for effective operation.

TRANSITIONS

We participated last year in the SEAS field measurement program groups from the University of Hawai'i, University of Washington and the University of Miami and have subsequently exchanged results and data with them.

RELATED PROJECTS

We worked with the researchers at the Hawai'i site that is operated by the University of Hawai'i by Dr. Anthony Clarke, Dr. Shiv Sharma and Dr. Volodia Kapustin. Our long-standing collaboration with Prof. Patricia Hull of Tennessee State University in the data analysis continues.

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